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ORIGINAL ARTICLE

Counting is a spatial process: evidence from eye movements

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Abstract Spatial–numerical associations (small numbers—left/lower space and large numbers—right/upper space) are regularly found in simple number categorization tasks. These associations were taken as evidence for a spatially oriented mental number line. However, the role of spatial–numerical associations during more complex number processing, such as counting or mental arithmetic is less clear. Here, we investigated whether counting is associated with a movement along the mental number line. Participants counted aloud upward or downward in steps of 3 for 45 s while looking at a blank screen. Gaze position during upward counting shifted rightward and upward, while the pattern for downward counting was less clear. Our results, therefore, confirm the hypothesis of a movement along the mental number line for addition. We conclude that space is not only used to represent number magnitudes but also to actively operate on numbers in more complex tasks such as counting, and that the eyes reflect this spatial mental operation.

Introduction

We constantly move and act in space. Through our sensorimotor experiences we become experts for spatial relations and we establish a space-based magnitude system (Walsh, 2003). Particularly, our sensorimotor experiences determine how we mentally structure and represent magnitude-related information in various conceptual domains, such as spatial or temporal extent (e.g., Barsalou, 2008; Casasanto & Boroditsky, 2008; Walsh, 2003, 2014). During the last decade, strong evidence has been accumulated that numbers are also represented spatially, with small numbers on the left and larger numbers on the right side in representational space (in Western cultures), thereby contributing to the concept of a "mental number line" (Fias & Fischer, 2005; Restle, 1970).

The pervasive small-left and large-right association is captured by the spatial–numerical association of response codes (SNARC) effect. This effect shows faster left-sided responses for small numbers and faster right-sided responses for large numbers when compared to the opposite magnitude-response pairing in various simple number processing tasks (Dehaene, Bossini, & Giraux, 1993; Hubbard, Piazza, Pinel, & Dehaene, 2005). Spatial–numerical associations have been well established in the horizontal dimension of space (see Fischer & Shaki, 2014a, for a recent review) and have recently been extended to vertical space, with small numbers being associated with the bottom and larger numbers with the top of a vertical line (e.g., Grade, Lefèvre, & Pesenti, 2012; Hartmann, Grabherr, & Mast, 2012b; Holmes & Lourenco, 2012; Ito & Hatta, 2004; Loetscher, Bockisch, Nicholls, & Brugger, 2010; Shaki & Fischer, 2012; Winter & Matlock, 2013). For example, when participants call out numbers at random, they produce smaller numbers during downward than during upward body motion (Hartmann et al., 2012b; Winter & Matlock, 2013).

Both horizontal and vertical spatial–numerical associations can be explained as the result of sensorimotor experiences: the horizontal association of numbers has been linked to reading and writing, as well as finger counting habits (e.g., Fischer, 2008; Fischer & Brugger, 2011;

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Göbel, Shaki, & Fischer, 2011; Shaki, Fischer, & Petrusic, 2009), and the vertical association seems to reflect the experience that "more" usually corresponds to higher positions in space (e.g., Fischer, 2012; Holmes & Lourenco, 2012; Lakoff & Johnson, 1980; but see also Hartmann, Gashaj, Stahnke, & Mast, 2014).

Numbers are omnipresent in our environment and the ability to deal with numbers is a key cognitive competence, with deficits causing far-reaching negative consequences, including reduced life prospects and increased health problems (e.g., Gross, Hudson, & Price, 2009; Parsons & Bynner, 2005). Thus, a better understanding of the spatial processes underlying numerical cognition has not only theoretical but also practical relevance.

A current question of interest is whether the spatial associations found during simple number processing tasks (e.g., magnitude and parity judgment tasks) are also involved in more complex number processing, such as counting and mental arithmetic (Fischer & Shaki, 2014a, b). Initial positive evidence has been found for approximate addition and subtraction of non-symbolic numerosities: participants perceived an incorrect solution with too many dots as correct in addition trials. Analogously, they perceived an incorrect solution with too few dots as correct in subtraction trials (McCrink, Dehaene, & Dehaene-Lambertz, 2007). When this finding is brought to bear on the notion of a mental number line, where small number entries are located to the left of larger number entries, then it suggests that mental addition is conceptualized as moving rightward, and mental subtraction as moving leftward along this number line, much as in the process of counting upward to compute addition results (Groen & Parkman, 1972). A general difficulty in stopping such imagined movements (known as representational momentum effect; e.g., Freyd & Finke, 1984; Hubbard, 2014) might then lead to the observed under- and overestimation biases with non-symbolic numerosities. This account of over- and underestimation of addition and subtraction results is referred to as operational momentum effect (Knops, Viarouge, & Dehaene, 2009; McCrink et al., 2007; see also Cassia, McCrink, de Hevia, Gariboldi, & Bulf, under review).

Turning now to exact arithmetic with symbolic numbers, there is recent evidence for a similar spatial arithmetic congruency effect (i.e., faster responses for the stimulus–response combinations leftward/downward—subtraction and rightward/upward—addition; see Anelli, Lugli, Baroni, Borghi, & Nicoletti, 2014; Lugli, Baroni, Anelli, Borghi, & Nicoletti, 2013; Marghetis, Nunez, & Bergen, 2014; Masson & Pesenti, 2014; Wiemers, Bekkering, & Lindemann, 2014). Nevertheless, the idea that a mental movement obligatorily accompanies our addition and subtraction processes remains controversial (Fischer & Shaki, 2014a, b). First, the overestimation of addition and underestimation of subtraction results can also be explained without referring to imaginary movements along a mental number line (Marghetis et al., 2014; for a discussion of alternative accounts see Fischer & Shaki, 2014a; Knops, Zitzmann, & McCrink, 2013, 2014). Second, it has been shown that the minus and plus signs alone can elicit left and right spatial biases, respectively (Pinhas, Shaki, & Fischer, 2014); this could have contributed to previous spatial–arithmetic congruency effects, at least in symbolic arithmetic tasks. Third, much of the previous evidence for spatial–arithmetic congruency effects involved overt spatial responses from participants (e.g., moving the arm leftward and rightward; see Marghetis et al., 2014; Pinhas & Fischer, 2008; Wiemers et al., 2014), or passive movements of participants through space (Lugli et al., 2013). These active or passive displacements could have triggered associated covert mental movements, such as a shift of attention along a sequentially ordered mental representation of numbers (e.g., Gevers, Santens, Dhooge, Chen, Bossche, & Fias, 2010; Hartmann et al., 2012a, b; see also Fischer & Shaki, 2015).

We, therefore, recently investigated spatial biases during mental arithmetic without inducing a particular spatial reference frame through lateral displacements by analyzing eye movements on a blank screen (Hartmann, Mast, & Fischer, 2015). Eye movements provide precise temporal and spatial information about participants' direction of attention (e.g., Altmann, 2004; Corbetta, Akbudak, Conturo, Snyder, Ollinger, & Drury, 1998; Grant & Spivey, 2003; Sheliga, Riggio, & Rizzolatti, 1994; Van Gompel, Fischer, Murray, & Hill, 2007). Eye tracking is, therefore, a promising research tool to study numerical cognition (Hartmann, 2015; Mock, Huber, Klein, & Moeller, under review), particularly given that eye movement control seems to interact with the processing of number magnitudes (e.g., Loetscher et al., 2010; Myachykov, Cangelosi, Ellis, & Fischer, 2015; or under review for this issue: Myachykov, Ellis, Changeolosi, & Fischer, under review; Ranzini, Lisi, & Zorzi, under review; Yu, Liu, Li, Cui, & Zhou, under review). Eye movements across a blank screen have previously been analyzed to study memory and mental imagery processes (e.g., Brandt & Stark, 1997; Johansson & Johansson, 2014; Johansson, Holsanova, & Holmqvist, 2006; Kennedy, 1983; Martarelli & Mast, 2011; Spivey & Geng, 2001) and language comprehension (e.g., Altmann, 2004; Huette, Winter, Matlock, Ardell, & Spivey, 2014). We think that this blank screen paradigm can reveal the spatial and temporal characteristics of mental processes in all domains where space is used to structure and represent information, even in seemingly abstract mental processes such as mental arithmetic or the processing of time (e.g., Hartmann, Martarelli, & Mast, 2014b; Hartmann et al., 2015; Stocker, Hartmann, Martarelli, & Mast, 2015; Winter, Marghetis, & Matlock, 2015).

In our previous study (Hartmann et al., 2015), participants solved auditorily presented arithmetic problems (e.g., 5 + 3) while looking at a blank screen, and the direction of their gaze shift when perceiving and solving these problems was used as indicator for spatial cognitive operations. We found two spatial biases in eye gaze during mental arithmetic: first, the eyes were directed more rightward when the magnitude of the first operand was large. More importantly, eye gaze was directed more upward when participants solved addition problems than when they solved subtraction problems. Crucially, inspecting the time course of this effect revealed that the latter bias emerged in the time window between the onset of the operator and the onset of the second operand, thus before the solution could be computed. The spatial bias during mental arithmetic found in our previous study was, therefore, induced by the operator ("plus" vs. "minus"), and not by the computational process (in which mental addition and mental subtraction takes place). Thus, it is still unclear to what extent eye movements reflect movements along a mental number line during arithmetic. A potential reason for the absence of evidence for covert movements during arithmetic computation in our previous study is that the covert movement mechanisms might be engaged in explicit counting tasks but not in mental arithmetic (cf. Carlson, Ayraamides, Cary, & Strasberg, 2007). Especially when arithmetic problems are easy, participants might retrieve the solutions directly from memory without engaging a counting mechanism (e.g., Andin, Fransson, Rönnberg, & Rudner, 2015; Ashcraft & Battaglia, 1978; Barrouillet & Lépine, 2005; Butterworth, Zorzi, Girelli, & Jonckheere, 2001; Campbell, 1994; Zbrodoff & Logan, 1990).

In the present study, we therefore focused on an explicit counting process: our participants counted upward or downward for 45 s (see Anelli et al., 2014; Lugli et al., 2013, for a similar approach) and we analyzed their gaze position on a blank screen. This approach had a further advantage over our previous study: in contrast to the previous task (Hartmann et al., 2015), the counting task no longer involved the presentation of an operator; therefore, any shift in gaze position could not be attributed to processing "plus" or "minus" but would rather reflect the spatial nature of counting. Thus, the modified task used in the present study, together with the eye tracking approach, will allow us to assess more appropriately whether and when a movement along the mental number line is involved in the mental manipulation of magnitudes.

Method

Participants

Twenty undergraduate psychology students participated for course credit (16 women, mean age 23.0, range 19–37 years, all right-handed by self-report). Participants gave written informed consent prior to the study which was approved by the local Ethics Committee. All participants had normal or corrected-to-normal visual acuity.

Apparatus and eye movement recording

Eye movements were recorded with an SMI RED© tracking system (SensoMotoric Instruments, Teltow, Germany). The tracking system had a sampling rate of 50 Hz, a spatial resolution of 0.1° and a gaze position accuracy of 0.5°. A 17-inch monitor (1280 × 1024 pixels) was used, and Experiment Center© Software and I-View© X Software were used to run the experiment and to record eye movements, both developed by SensoMotoric Instruments (SensoMotoric Instruments, Teltow, Germany). Fixations were extracted using Be-Gaze© software (SensoMotoric Instruments, Teltow, Germany) and were defined by a minimum duration of 80 ms (4 samples) and a maximal dispersion of 100 pixels.[1]

Task and procedure

Participants were seated 70 cm in front of the screen. A cover story was introduced to direct participants' attention away from their eye movements. A text appeared on the monitor screen, informing participants that previous studies found certain cognitive tasks have an influence on pupil size and that this experiment will further investigate this relationship. Thus, participants should think that their pupil sizes, rather than their eye movements, were recorded. They were also told that eye movements do not influence the pupil size (to prevent participants from staring at the same location during the whole task). After these instructions, a five-point calibration and validation procedure was performed (only error values below 0.8° were accepted) and then the actual task instructions appeared. Participants were instructed to count up in steps of 3 starting with 4 or to count down in steps of 3 starting with 80 for 45 s. Both tasks led to unfamiliar number sequences that cannot be easily retrieved from memory. Each participant performed both counting tasks (upward and downward) once, and the order of the two tasks was counterbalanced across participants. Participants were further instructed to continue

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[1] The algorithm checks the dispersion of consecutive data points in a moving window by summing the differences between the points' maximum and minimum x and y values ([max(x) – min(x)] + [max(y) – min(y)]). If the sum is below 100 pixels, the window represents a fixation and expands until the sum exceeds 100 pixels. The final window is registered as fixation with a duration corresponding to the interval between the timestamps of the first and last included sample. The centroid of the included points determines the x and y coordinate of the fixation.

counting if they made an error. There was no instruction whether participants should stop or continue to count when they eventually reached negative numbers in the downward counting condition.[2]

Before each block, a fixation stimulus appeared at the center of the screen (black cross in Arial font, size 20, on a gray background). When participants were ready to perform the task, they pressed the space bar and the fixation cross disappeared. During the 45-s counting period the gray screen remained blank. After the first block, a short break was provided and then the instructions for the second block appeared on the screen. The experimenter wrote down the numbers called out by the participant. The task was not repeated when a counting error was made, and the participant received no feedback about task performance. At the end of the experiment participants were asked whether they had an idea about the hypothesis.

Results

One participant correctly guessed the hypothesis of this study and was excluded from further analysis. Another participant had to be excluded due to poor recording (frequent blinks and bad recognition of the pupil by the eye camera lead to more than 50 % data loss). This left the data from 18 participants for statistical analyses. We describe performance in the counting task to document compliance with instructions before we report on participants' spontaneous eye movement behavior.

Counting performance

Participants made significantly more counting steps for upward than for downward counting (32.2 vs. 26.3), as revealed by a dependent *t* test; $t(17) = 5.06$, $p < .001$. It is a typical finding in mental arithmetic that addition is faster than subtraction (Ashcraft, 1992; Campbell, 2005). Counting errors were detected during six cases of upward counting and during five cases of downward counting. In all these cases, participants continued to count without notice of the error and no further deviation from the step size of three was detected after the error was made. The mean number of counting steps for trials with and without a counting error did not differ, as assessed by an independent-samples *t* test, $t(34) = -1.00$, $p = .324$, suggesting that counting errors do not reflect systematic differences in a speed–accuracy trade-off or compliance with the task. Thus, there was no reason to exclude trials with a counting error from further analyses.

Basic eye tracking results

Eye fixations outside of the screen were excluded from analysis (7.2 % of fixations). No other fixations were excluded from analysis. The mean fixation duration was slightly higher during downward compared to upward counting (693 vs. 616 ms) but this difference was not significant, $t(17) = -1.37$, $p = .188$. Interestingly, more fixations were made during upward than during downward counting [61.1 vs. 50.0, $t(17) = 2.60$, $p = .019$]. This is in line with previous studies reporting reduced saccade rates for more difficult arithmetic problems (Gao, Yan, &, Sun 2015; Nakayama, Takahashi, & Shimizu 2002; Siegenthaler, Costela, McCamy, Di Stasi, Otero-Millan, & Sonderegger, 2014).

Gaze position during counting

The spatial distribution of fixations during upward and downward counting is shown in Fig. 1. The mean horizontal screen position averaged over the entire counting period (45 s) was 77 pixels to the right of the screen center

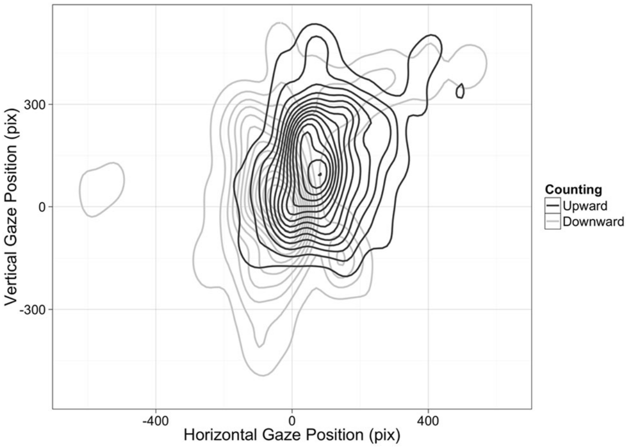

Fig. 1 Spatial distribution of fixations on the *blank screen* during *upward* (*black*) and *downward* (*gray*) counting. Mean gaze position was 111 pixels (pix) more *rightward* and 96 pix more *upward* during *upward* compared to *downward* counting

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[2] Seven participants indeed performed their last few downward counting steps in the negative range (on average 4.2 counting steps, which cover approximately 15 % of their counting time). Counting downward in the negative range is similar to counting upwards and might potentially influence the hypothesized mental movement. However, visual inspection of the last part of the gaze path during downward counting for these seven participants showed no systematically different pattern when compared to the terminal gaze path of the other participants, and these cases were not treated differently. From the 11 participants who did not reach the negative range, only two had the number "2" as final counting result (which is the last number before reaching the negative range). These two participants reached "2" at the end of their counting time, as noted by the experimenter, suggesting that no participant stopped counting when reaching zero.

for upward counting, and 34 pixels to the left of the screen center for downward counting. The difference of 111 pixels was highly significant, $t(17) = 5.04$, $p < .001$. When tested against zero (center of the screen), the rightward deviation during upward counting was significant, $t(17) = 3.57$, $p = .002$, but not the leftward deviation during downward counting, $t(17) = -1.00$, $p = .334$. Interestingly, the mean horizontal and vertical screen positions were not correlated, r (Pearson, $N = 18$) $= .044$, $p = .861$.

The mean vertical screen position was 130 pixels above the center of the screen for upward counting and 34 pixels above the center of the screen for downward counting. The difference of 96 pixels was significant, $t(17) = 2.20$, $p = .042$. When tested against zero (center of the screen), the upward deviation was significant for upward counting, $t(17) = 5.17$, $p < .001$, but not for downward counting, $t(17) = 0.90$, $p = .380$. Thus, participants look more rightward and upward during upward compared to downward counting.

Next we analyzed the temporal dynamics of this spatial bias. To this end, we averaged the raw horizontal and vertical eye position recordings for each second. Figure 2a and b shows the time course of horizontal and vertical eye positions over time, respectively. A linear mixed model approach instead of a repeated measure ANOVA was used to further evaluate these data because some cells of the factor combination counting and time were empty (i.e., not for all 1-s time windows there were fixations and the ANOVA would exclude participants with such missing values). We used R (R Core Team, 2014) and lme4 (Bates, Maechler, Bolker, & Walker, 2015) to perform linear mixed effects analyses for the horizontal and vertical screen position with counting (upward, downward), time (in s, 1–45), and the interaction between counting and time as fixed effects, and with participants as random intercepts [in lme4: gaze position $\sim$ counting $\times$ time + (1|subject)]. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. There was, however, a deviation from linearity for the vertical screen position: the residuals have a quadratic shape (cf. Fig. 2b). We, therefore, included an additional quadratic time variable (time^2, time^2 $\times$ counting interaction) into the model for the vertical screen position. Probability (p) values were obtained by likelihood ratio tests of the full model against the model without the effect in question (see for example Winter, 2013), using the R package "afex" (Singmann & Bolker, 2014). To keep the analysis equivalent to ANOVA, the covariates (time, time^2) were mean-centered, and the categorical predictor (counting) was sum-coded.

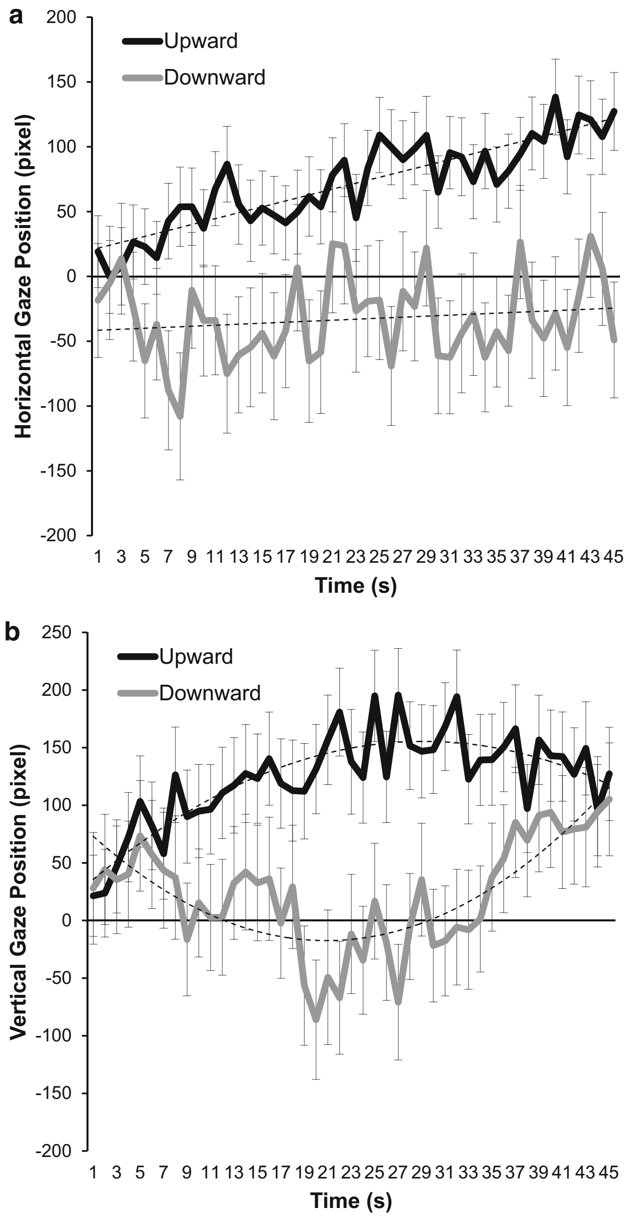

Fig. 2 Time course of the *horizontal* (**a**) and *vertical* (**b**) gaze position during *upward* (*black line*) and *downward* (*gray line*) counting. *Positive values* gaze positions on the *right* (**a**) and *upper* (**b**) screen half. *Error bars* ±1 SEM, and the *dotted lines* the *linear* (**a**) and *quadratic* (**b**) fits for the depicted means

For the horizontal gaze position, likelihood ratio tests confirmed a significant influence of counting, $\chi^2(1) = 225.74$, $p < .001$ (estimate $= 52.17$,[3] SEM $= 3.31$). Time was a significant covariate, $\chi^2(1) = 25.86$, $p < .001$ (estimate $= 1.27$, SEM $= 0.25$), and interacted with counting, $\chi^2(1) = 16.48$, $p < .001$ (estimate $= 1.01$, SEM $= 0.25$),

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[3] For sum-coded predictors (addition = 1, subtraction = −1), two times the estimate (104 pixels) reflect the mean difference between upward and downward counting. Note that this value is slightly different from the value we reported above (111 pixels); this difference is mainly driven by the different averaging procedure (over 1-s time points).

pointing to differences in the linear increase of horizontal gaze position over time for upward and downward counting. When tested separately for the two counting directions, likelihood ratio tests confirmed that time was only a significant covariate for upward counting, $\chi^2(1) = 82.69$, $p < .001$, but not for downward counting, $\chi^2(1) < 0.01$, $p = .972$.

For the vertical gaze position, the analysis also confirmed a significant influence of counting, $\chi^2(1) = 124.09$, $p < .001$ (estimate = 49.80, SEM = 4.35). There was neither a linear nor a quadratic relationship between the vertical gaze position and time (both $ps > .230$), but counting interacted with the linear time predictor, $\chi^2(1) = 45.82$, $p < .001$ (estimate = −9.10, SEM = 1.33), and also with the quadratic time predictor, $\chi^2(1) = 43.26$, $p < .001$. When tested separately for the two counting directions, likelihood ratio tests confirmed a significant quadratic relationship between time and the vertical screen position for both upward counting, $\chi^2(1) = 26.26$, $p < .001$, and downward counting, $\chi^2(1) < 22.05$, $p < .001$. The different quadratic relationships between time and the vertical gaze position for upward and downward counting are illustrated in Fig. 2b.

Before turning to an interpretation of our results, a further analysis addressed the concern that gaze position on a blank screen can be influenced by other factors than spatial–numerical associations (e.g., Ehrlichman & Micic, 2012; Kinsbourne, 1972). In other domains, it has been shown that cognitive effort is related to spatial biases in attention mechanisms (e.g., Lavie, 2005; Lepsien, Griffin, Devlin, & Nobre, 2005). Since upward and downward counting was associated with different levels of task difficulty (as indicated by more counting steps and more fixations for upward counting), a possible association between cognitive effort and gaze position could have contributed to our results. There is to our knowledge no study that analyzed the influence of task difficulty on gaze position on a blank screen.

To investigate whether there is a systematic space–difficulty relationship, we re-analyzed fixation position data on a blank screen for addition and subtraction trials in our previous study (Hartmann et al., 2015) and used pupil size as indicator of task difficulty. Pupil size typically increases with increasing cognitive effort (Kahneman & Beatty, 1966; for recent reviews see Binda & Murray, 2015, or Hartmann & Fischer, 2014), and increased pupil size has been found for more difficult arithmetic problems (e.g., Kahneman et al., 1969; Nakayama et al., 2002). Mean pupil size was computed from fixations that occurred after the auditory onset of the second operand until the end of the trial, i.e., the time interval during which arithmetic computations would have occurred. If cognitive load rather than spatial–numerical association determines gaze position, then pupil size should be a significant predictor of horizontal and vertical gaze position.[4]

To assess a possible space–difficulty association, we conducted another linear mixed effect analysis on the final horizontal and vertical gaze position with participant as random intercept factor and pupil size as fixed covariate, separately for addition and subtraction trials, using our previous dataset (Hartmann et al., 2015). The final gaze position was taken for each trial from the x and y coordinates of the last sample (when the response was given) of the time- and space-normalized gaze stream; for details, see Hartmann et al. (2015). Importantly, pupil size failed to predict the horizontal and vertical gaze position, for both addition and subtraction trials (all ps > .192). This additional analysis shows that cognitive load does not contaminate gaze position on a blank screen during mental arithmetic, and thus suggests that the effects found during counting in the present study can be attributed to spatial–numerical associations instead.

Discussion

In this study, we tested the hypothesis that counting upward is accompanied by a rightward and/or upward movement along the mental number line, and counting downward by a leftward or downward movement. The analysis of gaze position on a blank screen showed that gaze position during upward counting continuously shifted rightward, while no such shift was found during downward counting. With respect to the vertical dimension, gaze position followed an inverted u shape during upward counting: gaze position shifted upward during the initial phase of upward counting and shifted back toward the starting position during the later phase of counting. The reverse pattern was found for downward counting. Thus, our results partly confirm the idea of a movement along the mental number line during mental arithmetic and show that the eyes might be used to "act out" such a spatial process accompanying mental counting.

The association between counting and rightward/upward movement is in line with the idea of the operational momentum effect (McCrink et al., 2007; Knops et al., 2009), and with previous studies showing an arithmetic–

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[4] To validate the use of pupil size as indicator of cognitive effort, we first conducted another linear mixed model analysis with pupil size as fixed effect and participant as random intercept on response times, separately for addition and subtraction trials. Consistent with previous work (e.g., Kahneman et al., 1969; Nakayama et al., 2002), pupil size was a significant predictor of response times for both addition and subtraction trials (both ps < .001); response time increased with increasing pupil size, confirming that pupil size reliably reflects task difficulty.

space compatibility effect (Anelli et al., 2014; Lugli et al., 2013; Marghetis et al., 2014; Masson & Pesenti, 2014; Pinhas & Fischer, 2008; Wiemers et al., 2014). For example, Wiemers et al. (2014) found a facilitation of mental arithmetic when arm or eye movements were performed in a congruent way during arithmetic problem solving (leftward/downward for addition and rightward/upward for subtraction). Similarly, Lugli et al. (2013) reported that participants performed more upward counting steps when riding upward in an elevator, and more downward counting steps when riding downward in an elevator.

Interestingly, in our previous study (Hartmann et al., 2015), we did not find support from eye movements for a movement along the mental number line when solving simple addition and subtraction problems (e.g., $2 + 7$ or $9 - 5$). In that study, gaze position on a blank screen shifted more upward when processing “plus” than “minus” (see also Pinhas et al., 2014), but no movement was detected in the time period from the onset of the second operand until the response was given (i.e., during the actual computation process). Our previous results, therefore, suggested that solving simple arithmetic problems might not lead to movements along the mental number line. The fact that we did find evidence for such a movement in the present study clarifies that the counting task had critical characteristics for triggering a spatial process that the previous task did not have. In the previous task, the type of operation (addition vs. subtraction) was randomized for each trial, and the time needed to solve the problems was around 1 s (see Hartmann et al., 2015). Alternating between addition and subtraction trial-by-trial, as well as the short problem solving times (perhaps involving fact retrieval from memory) may have further limited the recruitment of a movement along the mental number line in that previous study. In contrast, the counting task employed in the present study required participants to continuously make mental increments or decrements[5] and the sequences were rather unlikely to be retrievable from memory. We think that these two aspects of the counting task allowed participants to use spatial strategies and to develop a dynamic spatial mental process over time, such as moving along a number line, to activate the successive number concepts. Indeed, we found that the spatial bias developed as a linear (or quadratic, respectively) function of time, and significant differences between upward and downward counting were found only after several seconds (see Fig. 2).

Moreover, it is possible that counting is more strongly related to space than mental arithmetic. When children learn to count, they spontaneously use their fingers (e.g., Alibali & DiRusso, 1999), and also adults often recruit their hands to count (e.g., when enumerating arguments in a speech). It has been suggested that the use of hands is highly related to the development of a mental number line (e.g., Fischer, 2008; Fischer & Brugger, 2011). Furthermore, counting implies a number sequence, which is closer to the concept of a mental number line than computing two numbers (which does not necessarily require conscious awareness of an ordered number sequence).

Nevertheless, spatial–arithmetic compatibility effects have also been found outside of counting tasks (Marghetis et al., 2014; Masson & Pesenti, 2014; Pinhas & Fischer, 2008; Wiemers et al., 2014). However, these tasks differed in other fundamental aspects from the settings of the present study. For example, the direction of motion or the spatial position of stimuli and responses was manipulated in these experiments and was, therefore, salient to participants. Attending to different movement directions or spatial locations, together with the involvement of the motor system in giving spatial responses, might facilitate the use of spatial strategies in mental arithmetic. In the present and in our previous study (Hartmann et al., 2015), no such spatial reference frame was induced, neither in the stimulus nor in the response. We argue that in this case, the spontaneous employment of a movement along the mental number line might be facilitated for continuous mental operations. In turn, finding evidence for spatial mappings is then more convincingly attributable to the cognitive mechanism of interest, as opposed to the measurement procedures (cf. Fischer & Shaki, 2015).

While we found a clear directional spatial bias for counting upward, our results do not confirm an equivalent spatial process during counting downward. When inspecting the time course of gaze positions, however, it can be seen that the gaze indeed shifted leftward within the first seconds of downward counting (see Fig. 2a). Similarly, the gaze also shifted downward in the first half of downward counting, reached a minimum at around 20 s, and then shifted upwards (see Fig. 2b). Thus, there is at least some evidence for a leftward and downward shift of gaze position from the early part of downward counting.

A possible explanation for the quadratic instead of linear pattern for the vertical gaze position (see Fig. 2b) might be that the involvement of mental computations was stronger at the beginning of counting: in the initial counting phase, participants were required to add or subtract 3 to reach the next solution. However, after a while, participants might become familiar with the unit-digit repetition throughout the sequence. In fact, the sequence of unit digits of the stated numbers is repeated after ten counting steps (4, 7,

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[5] Even though the counting task still requires alternating between addition and subtraction trials (as in Anelli et al., 2014; Lugli et al., 2013), participants performed continuous additions and subtractions within one trial before they switched to the other operation.

10, 13, 16, 19, 22, 25, 28, 31, 34, …). An increasing familiarity with the unit-digit sequence during counting might have biased participants' strategy from actual subtraction toward a retrieval strategy, and such a change in strategy might be accompanied by different spatial correlates. A possible change toward a repetition strategy may weaken the use of space in counting, and consequently upward and downward counting converge on the same average spatial location at the end of the counting period (at least for the vertical screen dimension). However, since we did not ask participants to report their strategies and strategy changes, and because a similar argument would apply to the upward counting task, this explanation remains speculative. Moreover, the fact that fewer (and tendentially longer) fixations were made during downward compared to upward counting might indicate that a less dynamic spatial process was engaged during the former condition. It might be possible that starting with lower numbers (in the range from 1 to 10, which is the predominant number range where SNARC effects are reported) in the upward counting condition leads to a stronger initial activation of a number line concept than starting with a larger number range in the downward counting condition.

Interestingly, other studies also found spatial–numerical associations only for upward and not for downward counting. Anelli et al. (2014) asked participants to walk straight ahead and then turn to the left or right while counting upward or downward (see also Shaki & Fischer, 2014). Participants made more upward counting steps after rightward than after leftward turns, but no difference was found for downward counting. Their results and ours suggest that it is not yet clear when and how space is involved in mental subtraction.

Our results may also contribute to the current discussion on whether the horizontal and vertical associations of number magnitudes are driven by the same or by different mechanisms (e.g., Fischer, 2012; Hartmann et al., 2014a; Holmes & Lourenco, 2012; Winter & Matlock, 2013; Winter, Matlock, Shaki, & Fischer, 2015). Our findings that (a) the horizontal and vertical gaze positions were not correlated and (b) that they followed different spatial trajectories over time (linear vs. quadratic) strengthens the view that different mechanisms might be responsible for the horizontal and vertical association of numbers (e.g., Fischer, 2012).

In this study, we attributed the rightward and upward drift in gaze position to movements along the mental number line. However, we cannot rule out completely that also other factors have contributed to this bias, such as the relative or absolute size of the numbers that were called out. Loetscher et al. (2010) showed that calling out a random number that was larger than the previous number was associated with a rightward and upward saccade, whereas calling out a number that was relatively smaller than the previous one was associated with a leftward and downward saccade. Accordingly, if only the relative size of the consecutive numbers would determine gaze position, we should have observed a continuous leftward and downward shift for downward counting. Similarly, downward counting started with higher absolute numbers (80, 77, …) and upward counting with smaller absolute numbers (4, 7, …). Thus, if calling out large absolute numbers leads to rightward/upward shifts, and calling out smaller absolute numbers to leftward/downward shifts, we should have observed the opposite pattern, especially at the beginning of the counting process (where in fact the addition—right/up and subtraction—left/down pattern was most pronounced). We also performed additional analyses showing that differences in difficulty between upward and downward counting cannot account for systematic differences in gaze position. We, therefore, think that the bias observed in this study reflects the spatial process accompanying mental addition.

In this study, it was possible for participants to reach the negative number range at the end of the downward counting period. Since we did not record participants' number sequences online, we were not able to match the exact time point of entering into the negative number range to the gaze position data. It might have been a good alternative to use higher starting numbers to avoid negative numbers (e.g., three digit numbers as used in Anelli et al., 2014; Lugli et al., 2013). However, for future research, it might also be interesting to explicitly correlate the transition from positive to negative numbers with eye movements to further investigate how negative numbers are represented (for a discussion see Fischer & Rottmann, 2005; Ganor-Stern, Pinhas, & Kallai, 2010; Tzelgov, Ganor-Stern, & Maymon-Schreiber, 2009; Varma & Schwartz, 2011).

To sum up, we extended previous research about spatial–numerical associations by showing that systematic spatial biases are also present during higher level cognitive operations on the mental number line, such as repetitive addition. Space is not only used to represent and structure more abstract concepts such as number magnitudes, it is also used to actively operate on numbers in more complex tasks such as counting and mental arithmetic.

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